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Key results from an *XMM-Newton* and *Chandra* study of a new sample of extreme ULXs from the 2XMM catalogue

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We present highlights from a study of a sample of 10 extreme-luminosity candidate ultraluminous X-ray sources ($L_X > 5 \times 10^{40} \text{ erg s}^{-1}$), all at distances $< 100 \text{ Mpc}$, identified from a cross-correlation of the RC3 catalogue of galaxies with the 2XMM catalogue. Five of the sample have also been observed by *Chandra*. Of the 10 sources, seven reside in the disc or arms of spiral galaxies, and the remaining three are close to large elliptical galaxies. Unlike many less luminous ultraluminous X-ray sources, temporal variability is observed on short (ks) and long (year) timescales for most sources in our sample. Long term spectral variability is also evident in some sources. In one case, we use archival *Chandra* data to demonstrate that a hyperluminous X-ray source candidate identified by *XMM-Newton* is actually resolved into multiple point sources at high spatial resolution, but note that the other candidates remain unresolved under *Chandra*'s intense scrutiny.

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1 Introduction

Ultraluminous X-ray sources (ULXs) are extra-nuclear X-ray sources with luminosities in excess of the Eddington limit of a stellar mass black hole ($L_X > 10^{39} \text{ erg s}^{-1}$). The physical nature of these intriguing objects remains open to debate (e.g., Miller & Colbert 2004, Roberts 2007). It was suggested by Colbert & Mushotzky (1999) that ULXs were powered by accretion on to intermediate-mass black holes (IMBHs) of mass 10^2 – $10^4 M_\odot$. This suggestion was supported by the detection of seemingly cool accretion disc components in the spectra of a number of ULXs, with apparent temperatures of ~ 0.1 – 0.3 keV indicating $\sim 1000 M_\odot$ black holes.

However the association of large numbers of ULXs with regions of rapid star formation (e.g., Fabbiano et al. 2001; Gao et al. 2003) implies that they are short-lived, hence require enough progenitors for multiple generations to be observed. The required number density would imply that an unfeasible proportion of galaxy mass would end up in IMBHs so it is much more likely that most ULXs harbour stellar remnant black holes (King 2004) and are either subject to beaming (geometric, King et al. 2001; relativistic, Körding et al. 2002) or accreting at super-Eddington rates.

Re-analyses by Gladstone et al. (2009), of a sample of ULX X-ray spectra chosen only on the basis of very high data quality ($\geq 10000 \text{ EPIC counts}$) have also brought into question the IMBH interpretation, instead identifying them with a previously unknown, presumably super-Eddington “ultraluminous” accretion state. This is consistent with the

consensus view that the majority of ULXs are increasingly likely to be powered by accretion onto small (up to $100 M_\odot$) black holes (e.g., Roberts 2007).

The above arguments do not preclude the possibility that a minority of ULXs are indeed powered by accretion onto IMBHs. Possibly the best IMBH candidates are the most luminous ULXs, with extraordinary X-ray luminosities in excess of $5 \times 10^{40} \text{ erg s}^{-1}$, including the hyperluminous X-ray sources (HLXs) with $L_X > 10^{41} \text{ erg s}^{-1}$. These extreme sources sit above the steep turn-off in the X-ray luminosity function of extra-nuclear sources (Grimm et al. 2003), below which sources can be explained by super-Eddington accretion rates onto stellar-mass black holes (King 2008) or larger (up to $100 M_\odot$) stellar remnants (Zampieri & Roberts 2009). Sources above the break require a combination of both larger black holes and super-Eddington accretion rates; or perhaps they harbour the elusive IMBHs. In order to investigate such a possibility, we present key results from a study of a new, small sample of some of the most extreme luminosity ULXs observed by *XMM-Newton* and *Chandra*.

2 The sample of extreme ULXs

The extreme ULX sample was retrieved from a catalogue of 475 ULX candidates in 240 galaxies (Walton et al. in prep.), produced by cross-correlating the RC3 catalogue of galaxies (de Vaucouleurs et al. 1991) with the 2XMM DR1 catalogue (Watson et al. 2009). From this catalogue twelve candidate ULXs observed by *XMM-Newton*, with $L_X > 5 \times 10^{40} \text{ erg s}^{-1}$ (based on the catalogued 2XMM flux) and within a distance of 100 Mpc were identified. The sample

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Table 1 ULX sample

ID	2XMM Source	Host Galaxy ^a	Galaxy Type ^b	Separation ^c "	Distance ^d Mpc	Peak Luminosity ^e $10^{40} \text{ erg s}^{-1}$
Src. 1	2XMM J011942.7+032421	NGC 470	SA(rs)b	33	32.7	$10.3^{+0.7}_{-1.1}$
Src. 2	2XMM J024025.6-082428	NGC 1042	SAB(rs)cd	96	18.9	$3.6^{+0.1}_{-0.2}$
Src. 3	2XMM J072647.9+854550	NGC 2276	SAB(rs)c	45	33.3	$6.1^{+0.4}_{-0.6}$
Src. 4	2XMM J120405.8+201345	NGC 4065	E	21	88	12 ± 3
Src. 5	2XMM J121856.1+142419	NGC 4254	SA(s)c	103	33.2	$8.9^{+0.7}_{-2}$
Src. 6	2XMM J125939.8+275718	NGC 4874	cD0	57	99.8	20 ± 4
Src. 7	2XMM J134404.1-271410	IC 4320	S0?	18	95.1	27 ± 3
Src. 8	2XMM J151558.6+561810	NGC 5907	SA(s)c: edge-on	102	14.9	4.2 ± 0.1
Src. 9	2XMM J163614.0+661410	MCG 11-20-19	Sa	16	96.2	7^{+2}_{-1}
Src. 10	2XMM J230457.6+122028	NGC 7479	SB(s)c	68	32.8	$6.1^{+0.3}_{-0.4}$

Notes: ^a Galaxy with which the candidate ULX was initially identified by the cross correlation. ^b Galaxy morphology from de Vaucouleurs et al. (1991). ^c Galaxy centre - ULX candidate angular separation (Walton et al., in prep.). ^d Galaxy distance used in the analysis. With the exception of src. 8, cosmology corrected distances based on redshifts from de Vaucouleurs et al. (1991) were used. For src 8., due to the requirement for local corrections the distance from Tully (1988) was used. ^e Peak observed 0.3 – 10 keV luminosity of the ULX candidates if at the identified host galaxy distance, based on spectral fits (see sec. 3.2).

was reduced to ten sources by the exclusion of M82 X-1 as it has been previously well studied and a probable spurious detection in NGC 4889 where it was unclear whether significant source counts were detected in excess of the clumpy galactic ISM.

Of the ten bright ULX candidates observed by *XMM-Newton*, and listed in table 1, three sources were previously identified as ULXs (src. 2, 3 and 5), and eight were present in multiple observations (the exceptions being src. 7 and 10 which were detected in only one *XMM-Newton* observation), including five sources detected by *Chandra* (src. 1, 3, 5, 6 and 9). Six of the sources were in the arms of spiral galaxies, one additional source was in an edge-on disc, and the remaining three sources were near to large elliptical galaxies (see table 1). The catalogued luminosities of four sources (src. 1, 4, 6, 7), including all three of the ULX candidates associated with elliptical galaxies, were consistent with HLXs¹.

3 Analysis and results

We detail the data reduction, and provide more detail on the analysis, in Sutton et al. (in prep.). Here we highlight some interesting results.

Four out of the five 2XMM ULX candidates imaged by *Chandra* remain point-like in appearance at higher spatial resolution (src. 1, 5, 6 and 9); however the object reported by Davis & Mushotzky (2004), here src. 3, is resolved into multiple point sources (Fig. 1). If at the distance of NGC 2276, all three sources are luminous enough to be candidate ULXs, although their total flux is less than that previously observed for the unresolved source by *XMM-Newton*. Clearly at least one of these sources was substantially more luminous during the earlier observation. The fact that short-term variability was detected in the unresolved

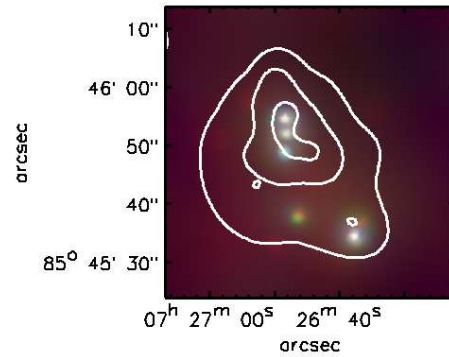


Fig. 1 Smoothed three colour *Chandra* image of the *XMM-Newton* region of src. 3, the candidate extreme ULX in NGC 2276, where the rgb colours correspond to 0.2–1.5, 1.5–2.5 and 2.5–8 keV. The image is overlaid with *XMM-Newton* contours, calculated from the smoothed *XMM-Newton* image of the source. Contours represent photon count levels of 10^0 , $10^{-0.5}$ and $10^{-1} \text{ ct pix}^{-1}$.

source (cf. Fig. 2) suggests that its flux was dominated by a single source.

Initial estimates from Walton et al. (in prep.) were for at most ~ 1 in 4 candidates with $L_x > 5 \times 10^{40} \text{ erg s}^{-1}$ to be background contaminants. For two of the sources candidate counterparts were identified implying that they are possible foreground or background contaminants (see below). Both candidate contaminant sources were initially associated with elliptical galaxies and were amongst the highest implied luminosity sources in our sample. Src. 7, in the elliptical galaxy IC 4320, remains as the most luminous detection and only object in an elliptical in the sample.

¹ Src. 3 was previously reported as a HLX (Davis & Mushotzky 2009) but the distance used here implies a lower luminosity.

The *XMM-Newton* error region of src. 4, the HLX candidate initially identified as being associated with NGC 4065, was shown to be coincident with SDSS J120405.84+2013-45.1 (star, Adelman-McCarthy et al. 2008) and SDSS J12-0405.83+201345.0 (QSO, Schneider et al. 2010). The 2–7.5 keV flux of src. 4 ($\sim 3.74 \times 10^{-14}$ erg cm $^{-2}$ s $^{-1}$) and R band magnitude of SDSS J120405.83+201345.0 (~ 19.8 , Schneider et al. 2010) combine to give an X-ray to optical flux ratio of ~ 1 consistent with an AGN (cf. Fig. 11 of Caccianiga et al. 2008) with the caveat that the spectrum and flux estimate of src. 4 may be contaminated by the nearby faint X-ray source 2XMM J120406.1+201406. We tentatively identify this HLX candidate as a contaminant, although *Chandra* data is required to confirm this.

The HLX candidate src. 6 was initially identified with NGC 4874. The *XMM-Newton* error region showed it may instead be associated with the smaller satellite galaxy SDSS J125939.65+275714.0. This was confirmed by a later *Chandra* observation (obs ID 10612), and its location ~ 3 arcsecs from the centre of the satellite galaxy maintained it as a good HLX candidate. However, an optical point source was identified, using *Hubble Space Telescope* (*HST*) Advanced Camera for Surveys/Wide Field Channel archived data, at the position of the HLX candidate. The source was therefore conservatively excluded as a possible contaminant, however we note that this may be revised after further examination of the *HST* data.

3.1 Variability

A characteristic of ULXs as a class is that they show little short-term variability – for example Swartz et al. (2004) found that only 5–15% of ULX candidates displayed detectable variability on time scales of 1 ks, and Heil et al. (2009) showed that variability is suppressed in a number of high quality ULX datasets in the 10^{-4} – 1 Hz frequency range, many of which are limited by lack of statistics or lack of monitoring observations. To test for variability, light curves of the sample ULXs were binned on time scales such there were ~ 25 counts per element of temporal resolution. Fractional variability (calculated using the method of Vaughan et al. 2003) was detected in a total of 10 detections of 6 sources out of the 8 remaining sources (Fig. 2) albeit mainly at low significance. Similar levels of variability could not be ruled out in the remaining two sources. If variability is common amongst extreme ULXs, we could be observing variability in excess of that expected from a linear rms variability – flux relation (cf. Heil & Vaughan 2010).

Src. 1, 3 & 5 were present in multiple observations and were observed to vary in luminosity, by factors ~ 1.5 –7 between detections (Fig. 3). Interestingly, in a number of sources with multiple observations, the peak luminosity is not sustained, e.g., src. 1 decreases from the hyperluminous regime to a more typical high ULX luminosity.

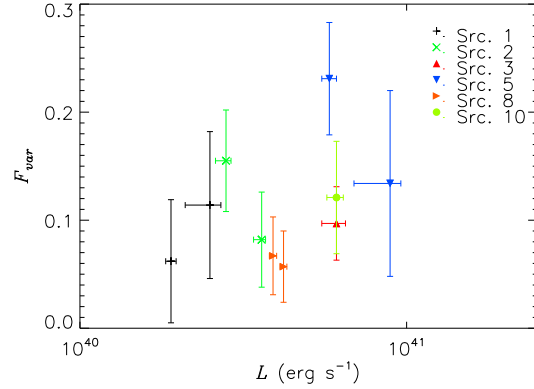


Fig. 2 Excess fractional variability of ULX candidates in which variability was detected at greater than 1σ significance.

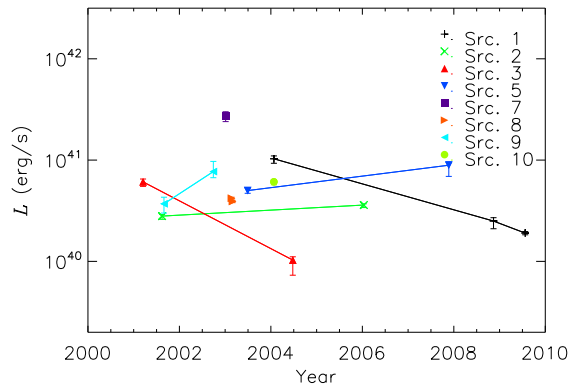


Fig. 3 0.3–10 keV *XMM-Newton* & *Chandra* absorbed luminosities of ULX candidates (excepting those that have been excluded as possible contaminant objects) for observations with greater than 100 counts. For the later observation of src. 3 the brightest of the resolved point sources is plotted.

3.2 Spectral analysis

Absorbed power-law and multi-colour-disc blackbody spectral models (powerlaw and diskBB in XSPEC) were fitted to data with > 250 counts using χ^2 statistics and > 100 counts using Cash-statistics (Cash 1979). Two absorption components were included, one fixed to the Galactic foreground column density (Dickey & Lockman 1990), the other free. A power-law model is not rejected at the 3σ level in any observation. Power-law spectral fits had typical intrinsic absorption columns of ~ 0.1 – 1×10^{22} cm $^{-2}$ and generally fairly hard photon indexes of 1.5–2.2. For perspective, typical values of spectral parameters derived from ULX samples over a more complete luminosity range are: $N_H \sim 0.09$ – 0.57 , 0.02 – 3×10^{22} cm $^{-2}$ and $\Gamma \sim 1.6$ – 3.3 , 0.8 – 4 (Gladstone et al. 2009; Bergeha et al. 2008). Swartz et al. (2004) found $\langle \Gamma \rangle = 1.74 \pm 0.03$ for their sample of *Chandra* ULX observations, with a minority of sources (20 out of 130) having

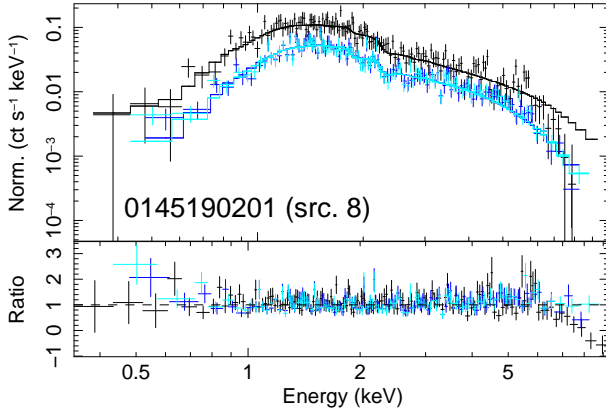


Fig. 4 Power-law fit to *XMM-Newton* EPIC detection of src. 8, the extreme ULX candidate in spiral galaxy NGC 5907. A spectral turn-over at ~ 6 keV is clearly visible.

$\Gamma > 3$. The sample presented here is interesting in that it appears to be consistent with the trend observed in the sample of Berghea et al. (2008), that the brightest ULXs are spectrally harder than less luminous ULXs.

Thermal (disc-dominated) spectra were statistically preferred (although power-law models could not be rejected in any detection) in the most luminous observation of src. 1, in 2 of the 3 resolved sources in the later observation of src. 3, and the later observation of src. 8. Disc temperatures varied between ~ 1.0 – 1.6 keV, similar to temperatures seen in other luminous ULXs (when modelled as a multi-colour-disc, e.g., 1.1 – 1.8 keV, Makishima et al. 2000) and in galactic black hole binaries in the thermal dominated state. However, with the moderate to low quality X-ray data available it might not be possible to discriminate between a thermal and ultraluminous state model (Gladstone & Roberts 2009).

Observations of src. 8 – with clearly the best X-ray data in the sample – contain significant evidence of a high energy spectral break (Fig. 4). Following the analysis of Stobbart et al. (2006) the high energy 2–10 keV spectrum (over which absorption is negligible) was fitted with both a standard and a broken power-law. The broken power-law gives a significant improvement in both observations (F-test probabilities of 1×10^{-12} and 4×10^{-8}) with break energies of $5.9^{+0.4}_{-0.2}$ and $6.5^{+0.3}_{-0.4}$ keV for the first and second observations respectively, an observational signature of the ultraluminous state (Gladstone et al. 2009). Thus it appears the ultraluminous state (*i.e.*, super-Eddington accretion) is still present in at least one ULX in the sample.

Variability in spectral index was also studied (Fig. 5). The sample appears to possess heterogeneous behaviours. The spectra of src. 1 and 8 are softer at increased luminosities, whereas that of src. 2 and 3 clearly harden at higher luminosities (the brightest resolved *Chandra* source at the position of src. 3 is plotted, although the same is true for all 3 resolved sources). This variety of behaviours is redolent of what we observe in lower-luminosity ULXs (*cf.* Kajava & Poutanen 2009; Feng & Kaaret 2009).

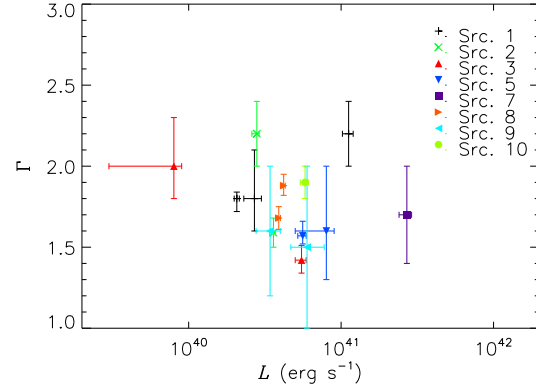


Fig. 5 Power-law photon index plotted against luminosity for ULX candidate observations with greater than 100 counts. 90% errors are shown for spectral index.

4 Discussion

Although X-ray data for this sample of ULXs is of limited quality, a number of interesting insights can be drawn. The extreme sources in this sample tend to have spectra at the hard end of the range observed in lower luminosity ULXs. This could be interpreted by a direct comparison with Galactic black hole binaries (BHBs) as being in a low/hard state, tending to support the IMBH hypothesis. However such an interpretation of the X-ray spectral evidence may be naïve as it has been shown that a sample of high quality ULX spectra reject such models (Gladstone et al. 2009). The success in fitting an absorbed power-law spectral model to the sample observations may be a reflection of the lack of data.

We find evidence of a high energy spectral break in src. 8. Such a spectral feature has been identified as the key signature of the proposed ultraluminous state in ULXs. Its presence in this highly luminous source not only provides evidence against the low/hard state interpretation, but further indicates that this extreme source may be drawn from the same population as the less luminous sample of Gladstone et al. (2009). As the ultraluminous state likely occurs at much greater Eddington ratios than are seen in the low/hard state, this negates the requirement for an IMBH, at least in this source.

The sample sources tend to be variable on short time-scales to a degree greater than would be expected from linear scaling with flux from less luminous ULXs. High levels of variability are seen in Galactic BHBs in the low/hard state, however the notable increase in variability between ‘normal’ ULXs and this sample may actually be attributable to the suppressed variability identified in Heil et al. (2009) only being present in less luminous sources.

Similarly to lower luminosity ULXs, most of the sample sources reside in spiral galaxies. Src. 1 is observed to drop in luminosity by a factor of ~ 5 from the hyperluminous regime to $\sim 1.9 \times 10^{40} \text{ erg s}^{-1}$. Such behaviour is not atyp-

ical of other well studied HLXs – ESO 243-49 HLX 1 has been reported to vary in luminosity over \sim days by a factor of ~ 21 (Godet et al. 2009), Wolter et al. (2006) report a factor of 2 dimming in the HLX candidate in the Cartwheel galaxy over 6 months and Ptak & Griffiths (1999) report a factor of 4 reduction in the luminosity of M82 X-1.

In summary there are indications of a number of similarities between the sample of highly luminous ULXs presented here and less luminous sources – for example, there is a preference for spiral galaxy hosts, and heterogenous spectral variability with luminosity is observed in both. Large changes in luminosity between observations are seen in the sample, suggesting that the extreme brightnesses observed may be a transient phenomenon. Src. 3 in particular decreases in luminosity such that it is indistinguishable from other less-luminous ULXs. However, some differences are evident; unlike less luminous ULXs there is no evidence of suppressed variability, or of a minority of spectrally soft sources (although with the latter point in particular this may be due to the small sample size). Further, deeper observations of this interesting sub-class of ULXs are therefore required to improve our understanding of these extraordinarily luminous objects.

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